NAIC-ID(RS)T-0577-95

NATIONAL AIR INTELLIGENCE CENTER

RESEARCH ON LASER DAMAGE THRESHOLD OF PHOTOELECTRIC DETECTORS

by

Chen Dezhang, Zhang Chengquan, et al.

Approved for public release: distribution unlimited

HUMAN TRANSLATION

NAIC-ID(RS)T-0577-95 13 February 1996

MICROFICHE NR: 96C000088

RESEARCH ON LASER DAMAGE THRESHOLD OF PHOTOELECTRIC DETECTORS

By: Chen Dezhang, Zhang Chengquan, et al.

English pages: 10

Source: Jiguang Jishu, Vol. 19, Nr. 3, June 1995; pp. 135-140

Country of origin: China
Translated by: Leo Kanner Associates
F33657-88-D-2188
Requester: NAIC/TATD/Bruce Armstrong
Approved for public release: distribution unlimited.

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE NATIONAL AIR INTELLIGENCE CENTER.	PREPARED BY: TRANSLATION SERVICES NATIONAL AIR INTELLIGENCE CENTER WPAFB, OHIO

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

RESEARCH ON LASER DAMAGE THRESHOLD OF PHOTOELECTRIC DETECTORS

Chen Dezhang, Zhang Chengquan, Qing Guangbi,
Liu Yun, Ye Zhusheng, Li Lin, and Guo Yong

Southwest Institute of Technical Physics
Chengdu 610041

Abstract: The perpetual laser damage effects of silicon PIN photoelectric diodes and silicon avalanche photodiodes irradiated by a laser of $1.06\mu m$ or $0.53\mu m$ wavelength are studied. The laser damage thresholds of the detectors are experimentally measured. The main reason of causing the perpetual damage are the laser heat singe on the PN connect of photoelectric diodes. The damage thresholds are relative to the laser wavelength, pulse width and the photodiod structure.

Key words: photoeletric detector perpetual laser damage threshold

I. Introduction

With features of high sensitivity, low noise, small size, and light weight, photoelectric detectors are extensively applied in military and civilian fields. The photoelectric detectors are very easily jammed or damaged by high-powered lasers and therefore there is important practical significance in studying the damage effects and damage thresholds of lasers acting on photoelectric detectors. The article studies mainly the permanent damage effect by lasers with respect to detectors (such as selection PIN photoelectric diode and silicon avalanche photoelectric diodes) and measures the density threshold value of damage.

II. Theory and Analysis

The permanent damage caused by a laser on a photoelectric detector indicates the critical damage to such detector by a high-powered laser so that the detector cannot operate normally, and the damage is irreversible; this is called hard damage. As discovered experimentally, after laser damage on the photoelectric detector, its properties degenerate, such as lowering of responsivity R, increase in dark current, lowering of reverse-direction resistance, and rise in noise, among other properties. By using responsivity R as the evaluation indicator of permanent damage, under conditions of single damage, if the responsivity of the detector drops to less than 20% of the original value, this is considered as permanent damage to the detector. From the operating principle of PIN diodes and silicon avalanche photoelectric diodes, we know that the two important processes of the photoelectric effect of silicon PIN photoelectric diodes are generation of photo carrier pairs and the multiplication and separation of carriers in the PN junction avalanche zone. Both processes must coexist. In the authors' view, the separation of the carrier pairs during the photoelectric effect is the weaker. The permanent damage done by the laser on the photoelectric detector is the destruction of the separation process of carriers, so that there is a weakening or loss of the capability of the separated carrier pairs. This is destruction at the PN junction, so that the electric field of the carriers collected by the photoelectric detector weakens, or even no collecting electric field can be built up. As to the cause, the authors presented a damage mechanism in which an electric leakage path forms due to separation and redistribution of impurity atoms in the molten silicon material. Since the temperature increase is caused by semiconductor absorption of light energy, when the temperature exceeds the melting point, the material melts. After cooling down, the material quickly crystallizes. On the solid-liquid interface with rapid motion, high-concentration aggregation zone of impurity atoms forms.

These high-concentration zones result in an electric leakage path (dopant-enriched high-conductivity path). If the electric leakage channel penetrates the PN junction (in other words, the PN junction is punctured by heat) to establish an intensive electric field not collecting carriers, in this case, although the photocarriers are generated, yet these carriers are unable to be immediately collected, thus not contributing to photocurrent. If the electric leakage path only narrows the width of the PN junction, and the carrier collecting electric field is weakened, this is manifested as lowered responsivity. For the same reason, with respect to the silicon avalanche photoelectric diodes, an aggregation of impurity atoms forms an electric leakage path to hinder the buildup of the avalanche amplified electric field, thus basically there is no multiplication function by the avalanching, and the avalanche diodes lose their action. If the electric leakage path penetrates the PN junction (similarly as the heat puncture on the PIN diodes) and is unable to collect carriers, there is basically no responsivity to the incident light. Thus, the temperature at the PN junction of the photoelectric diode reaches the melting point, which is the necessary condition for attaining permanent damage.

The laser thermal effect is the main effect in the interaction process between laser and semiconductor, relating to the heat energy process of generation, buildup, and conduction. From the temperature distribution function on the semi-infinite solid surface, due to the heat conduction equation and the instantaneous circular ring heat source [2] to induce the function of a gaussian light beam the temperature distribution function T in the conductor is

$$T = \frac{\alpha d^2(1-R')e^{-\alpha z}P_0}{\sqrt{\pi}Kk^{-1/2}}\int_0^t \frac{P(t)\mathrm{d}t}{t^{1/2}(4kt+d^2)}\exp\left[-\frac{z^2}{4kt}-\frac{r^2}{4kt+d^2}\right] \qquad (1)$$

In the equation, α is the absorption coefficient of the laser by the material; R' is the surface reflectivity; K and k are, respectively, the heat conductivity and heat diffusion coefficient of the material; d is √2 times the light spot radius;

P_0 is the peak power density; P(t) is the pulse normalization function; t is the effective acting time of the laser pulse; r and z are the cylindrical coordinates functions, while r is the distance from the central axis, and z is calculated from the incident surface to the point of origin. Let r=0 in order to obtain the temperature distribution function T_{center} on the central axis, that is:

$$T_{center} \frac{2d^2P_0(1-R')e^{-\alpha z}}{\sqrt{\pi}Kk^{-1/2}}\int_0^t \frac{P(t)dt}{t^{1/2}(4kt+d^2)}\exp(-\frac{z^2}{4kt}) \tag{2}$$

Since the temperature of the PN junction at the melting point is the necessary condition for permanent damage to the photoelectric detector, assuming that the distance between the incident surface and the PN junction is a, and the melting temperature is T_{th}, from Eq. (2) we can obtain the peak power density threshold P_{th} and the energy density threshold E_{th} for permanent damage, that is,

$$\begin{cases} P_{th} = \dfrac{KT_{th}\sqrt{\pi}e^{\alpha a}}{ad^2\sqrt{k}(1-R')\int_0^t \frac{P(t)\exp(-a^2/4kt)}{t^{1/2}(4kt+d^2)}dt} \\ E_{th} = \dfrac{K\tau T_{th}\sqrt{\pi}e^{\alpha a}}{ad^2\sqrt{k}(1-R')\int_0^t \frac{P(t)\exp(-a^2/4kt)}{t^{1/2}(4kt+d^2)}dt} \end{cases} \tag{3}$$

In the equation, τ is the semi-width of the laser pulse. We know from Eq. (3), P_{th}, E_{th} are proportional to eaα, in other words, the greater the distance from the incident surface to the PN junction, the more difficult it is for damage to occur. If the absorption coefficient α is increased, the damage density threshold decreases. The damage density thresholds P_{th} and E_{th} are related to α and τ, as well as to the structure of the photoelectric detector. To simplify Eq. (3) and to assume that P(t) is always 1, and let a approach 0, we can obtain the result that P_{th} and E_{th} are:

$$\begin{cases} P_{th} = K\sqrt{\pi}T_{th}/\alpha d(1-R')\mathrm{arctg}(4k\tau/d^2)^{1/2} \\ E_{th} = K\tau\sqrt{\pi}T_{th}/\alpha d(1-R')\mathrm{arctg}(4k\tau/d^2)^{1/2} \end{cases} \tag{4}$$

If $4k\tau >> d^2$, then $\mathrm{arctg}(4k\tau/d^2)^{1/2} \approx \pi/2$, , therefore P_{th} and E_{th} are

$$\begin{cases} P_{th} = 2KT_{th}/\alpha d(1-R')\sqrt{\pi} \\ E_{th} = 2K\tau T_{th}/\alpha d(1-R')\sqrt{\pi} \end{cases} \tag{5}$$

If $4k\tau << d^2$, then $\mathrm{arctg}(4k\tau/d^2)^{1/2} \approx 4k\tau/d^2$, therefore P_{th} and E_{th} are:

$$\begin{cases} P_{th} = dK\sqrt{\pi}T_{th}/4k\alpha(1-R')\tau \\ E_{th} = dK\sqrt{\pi}T_{th}/4k\alpha(1-R') \end{cases} \tag{6}$$

From Eqs. (5) and (6), with respect to the detector in which the PN junction is at a very shallow site under the incident surface with long pulse ($4k\tau >> d^2$) damage, the power density threshold is not related to τ, and the energy density threshold is proportional to τ. In the case of short pulses ($4k\tau << d^2$) damage, the power density threshold is inversely proportional to τ. The energy density threshold is not related to τ.

III. Experiments and Results

Fig. 1 is the block diagram on the experimental principle. In the diagram, an He-Ne laser is used to align the optical path. There are two kinds of laser wavelengths in the damage experiment--1.06μm and 0.53μm. The pulse width for the 1.06μm laser is 20ns and 60μs, respectively. The pulse width of an 0.53μm laser is 20ns. The adjustable laser power supply and the mutual attenuators I and II are used to adjust the incident laser energy for damage. A sampling plate and a laser energy ratio meter are used for real-time monitoring of incident laser energy. A focusing lens is used to converge the laser beam, with focal length at 70mm (1.06μm). A precision microammeter is used to monitor the dark current. The photoelectric detectors are SPD-001, SPD-002, SPD-005 silicon photoelectric diodes and SPD-032 silicon avalanche diode. The SPD-001 and SPD-002 are of the $p^+p^-n^+$ structure; the dimension of the photosensitive surface is OD0.8mm; however, the SPD-002 surface is subjected to honeycomb shape treatment. The SPD-005 is of the $p^+n^-n^+$ structure; and the dimensions of the

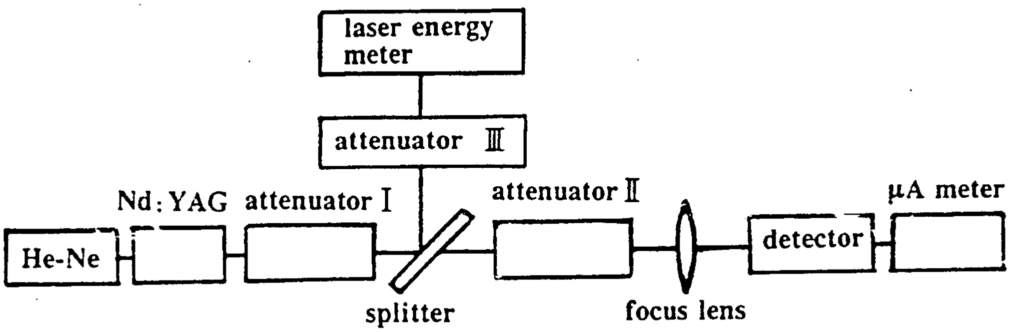

Fig. 1 Experimental block diagram

photosensitive surface are 3.5mm x 3.5mm. The SPD-032 is of the $p^{+}pp^{-}n^{+}$ structure; and the dimension of the photosensitive surface is OD0.8mm. In the experiments, the photoelectric detector is near the focal plane of the focusing lens. The half-intensity light spot diameter at the photosensitive surface is recorded by a photographic negative. A reading microscope is used to measure the size of the singe light spot. Table 1 shows the experimental results. Table 2 shows the performance comparison of a photoelectric detector before and after damage.

As experimentally found, for the damage to the photoelectric detector caused by a 60μs laser pulse, the regular circular melted pits can be seen on the photosensitive surface. In addition, there is much splash material adhering around the pits, and recrystallized small mounds can be seen in the pits, as shown in Fig. 2. However, in the case of permanent damage to the photoelectric detector caused by a 20ns laser pulse, there are irregular shallow pits on the photoelectric surface, generally appearing as vaporized pits. Many minute mounds are distributed in the pits, possibly due to local vaporization. In addition, loud cracking sounds were heard and cracks appear on the photoelectric surface as shown in Fig. 3. In measuring the I-V properties of the photoelectric detector, the performance deviates quite sharply from that of diodes, with the reverse-

Table 1 Damage density threshold for photo-electric detector

wavelength (μm)	pulse-wideth	number	diameter (mm)	energy density threshold (J/cm^2)	power density threshold (W/cm^2)	phenomenon
1.06	20ns	SPD-001-12	Ø0.8	64.8	3.23 × 109	the surface of detectors are marked by small mounds and irregular shallow pit. The loud burst sounds are heard.
1.06	20ns	SPD-005-10	3.5×3.5	31.5	1.58 × 109	the same above
1.06	20ns	SPD-005-21	3.5×3.5	26.8	1.32 × 109	the same above
1.06	20ns	SPD-032-7	Ø0.8	64.3	3.22 × 109	the same above
1.06	60μs	SPD-001-13	Ø0.8	43.7	7.28 × 105	the surface of detectors are marked by deeper circular pit resolified mounds and splash material. No burst sounds
1.06	60μs	SPD-001-15	Ø0.8	42.3	7.05 × 105	the same above
1.06	60μs	SPD-002-5	X0.8	32.4	5.40 × 105	the same above
1.06	60μs	SPD-005-9	3.5×3.5	36.3	6.05 × 105	the same above
1.06	60μs	SPD-032-8	Ø0.8	47.6	7.93 × 105	the same above
0.53	20ns	SPD-001-11	Ø0.8	5.6	2.80 × 108	the photo-sensitive surface of detectors are marked by white damage spot. No burst sounds
0.53	20ns	SPD-032-4	Ø0.8	4.92	2.46 × 108	the same above

direction resistance dropping by several orders of magnitudes. Even the PN junction becomes pure resistive performance, with serious damage to the PN junction of the photoelectric diode, with a fairly large drop in the responsivity, even sometime without any responsivity. With respect to permanent damage to the photoelectric detector by the 0.53μm laser, the damage spots can be seen on the photosensitive surface; these are not damage pits, without any clear cracking sounds having been heard, as shown in Fig. 4.

IV. Conclusions and Analysis

1. The permanent damage to the photoelectric detector by the laser is mainly thermal damage, with phenomena of stress, melting, and vaporization. There are cracks, molten pits, and vaporized pits on the photosensitive surface, in addition to splash material adhering to the surface surrounding the pits. the responsivity of the photodetector is seriously deteriorated,

there being almost no responsivity with respect to incident light.

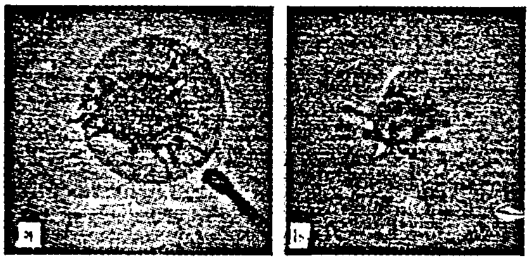

Fig.2 Photograph of the surface of the damaged detector by 1.06μm, 60μs laser pulse (100$^{\times}$)
a - SPD - 001 100times b - SPD - 005 100times

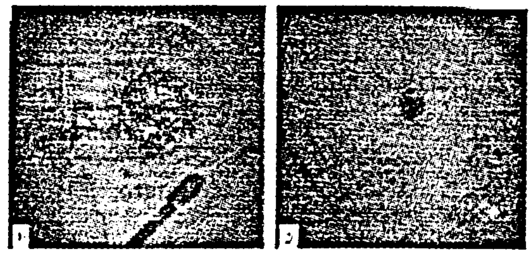

Fig.3 Photograph of the surface of the damaged detector by 1.06μm, 20ns laser pulse (100$^{\times}$)
a - SPD - 032 100times b - SPD - 005 40times

2. The permanent damage to the photoelectric detector by the laser is mainly the destruction of the PN junction, forming a zone of electric leakage path with a high concentration of impurity atoms so that the width of the PN junction narrows, or even leading to thermal puncturing, causing weakening of the high electric field for carrier collection or the avalanche electric field. Or, the high electric field for carrier collection or the avalanche electric field is not established. Therefore, the position of the PN junction has a greater effect on the capability of damage resistance by the photoelectric diode. Since the PN junctions of the SPD-001 and SPD-032 are at deeper sites beneath the incident surface, the damage density threshold is the highest, and approximately equal to the damage threshold; this proves that the structures are similar. Since the PN junction of the SPD-005 photoelectric detector is at a shallower site beneath the incident surface, the damage density threshold is smaller. We can see that the experimental results are consistent with theory.

3. With respect to the photoelectric detectors (such as SPD-001 and SPD-032) with the PN junction at a deeper site beneath the incident surface, the damage density threshold due to

Table 2 Characteristics comparison of photo-electric detector

Number	before damage I_d (nA)	before damage R_1 (Ω)	before damage R_2 (MΩ)	before damage responsivity (A/W)	after damage I_d (mA)	after damage R_1 (Ω)	after damage R_2 (Ω)	after damage responsivity (A/W)
SPD-001-12	20	300	>20	0.16	2.0	10	10	No singal
SPD-005-10	8	85	>20	0.79	4.0	43	43	0.026
SPD-005-21	9	85	>20	1.5	1.4	85	2.0×10^5	0.228
SPD-032-7	60	80	>20	>11	2.0	75	5.5×10^3	No singal
SPD-001-13	10	100	>20	0.17	4.0	7	7	No singal
SPD-001-15	20	80	>20	0.15	2.8	72	5.5×10^4	No singal
SPD-002-5	10	95	>20	0.53	4.0	10	10	No singal
SPD-005-9	18	150	>20	0.74	4.0	20	20	No singal
SPD-032-8	60	80	>20	>11	2.0	44	44	No singal
SPD-032-4	60	85	>20	>11	1.5	80	6.2×10^3	No singal
SPD-001-11	10	85	>20	0.16	2.0	84	9.0×10^3	No singal

a 20ns laser pulse is greater than the damage energy density threshold due to a 60μs laser. This is so because plasma is generated in the mutual action process between the 20ns high-powered laser and the semiconductor, since plasma absorbs light energy, with a certain protection. However, with respect to the SPD-005 photoelectric diode, there is little difference in the energy density threshold for both kinds of pulse function with the power density threshold of short pulses being much greater. Because the PN junction of the SPD-005 photoelectric diode is at a very shallow site beneath the incident surface (a approaches 0), and two kinds of pulses of 20ns and 60μs both satisfy the condition that $4k\tau \ll d^2$. From Eq. 6, E_{th} is not related to τ, and P_{th} is proportional to τ^{-1}. Thus we can see that the experimental results are consistent with theory.

4. The damage density threshold on a photoelectric detector acted on by a 0.53μm laser is much smaller than for a 1.06μm laser. This is because the absorption coefficient of the 0.53μm laser on semiconductor material is much greater than that of the 1.06μm laser.

With regard to the foregoing, we know that a laser is related to the damage density threshold and wavelength λ of

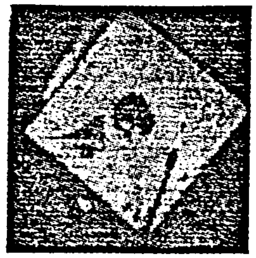

Fig. 4 Photograph of the surface of the damaged detector by $0.53\mu m$, 20ns laser pulse ($40^{\times}$).

the photoelectric detector, along with the pulse width τ and the detector structure.

The authors express their sincere gratitude to researchers Yang Jingchu, Wen Xuedong, and Hou Lianzheng, senior engineers Pu Shude, and Gou Xizhen for their assistance and, in some cases, guidance.

The article was received for publication on July 27, 1994.

As a brief introduction to the first-named author Chen Dezhang: male, born in November 1964, with a master's degree. He engaged in research on laser technology from the outset of his career.

REFERENCES

1 Gimlionl J F, Marquard C L. J A P, 1974;45(11):4993~4996

2 Ready J F. Effects of high-power laser radiation. New York, London: Academic Press, 1971:76

DISTRIBUTION LIST

DISTRIBUTION DIRECT TO RECIPIENT

ORGANIZATION	MICROFICHE
B085 DIA/RTS-2FI	1
C509 BALLOC509 BALLISTIC RES LAB	1
C510 R&T LABS/AVEADCOM	1
C513 ARRADCOM	1
C535 AVRADCOM/TSARCOM	1
C539 TRASANA	1
Q592 FSTC	4
Q619 MSIC REDSTONE	1
Q008 NTIC	1
Q043 AFMIC-IS	1
E404 AEDC/DOF	1
E410 AFDTC/IN	1
E429 SD/IND	1
P005 DOE/ISA/DDI	1
1051 AFIT/LDE	1
PO90 NSA/CDB	1

Microfiche Nbr: FTD96C000088
NAIC-ID(RS)T-0577-95